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ABSTRACT

We present the first results from an experimental campaign to measure atomic ablator-gas mix in capsule implosions on the National Ignition Facility. Plastic capsules containing CD layers were filled with Tritium gas; as the reactants are initially separated,

DT fusion yield provides a direct measure of mix. Capsules were imploded with x-rays generated in hohlraums with peak radiation temperatures of ~294 eV at a moderate convergence ratio of ~15. While the TT fusion reaction probes conditions in the central part of the implosion core, the DT reaction probes a mixed region on the outer part of the core. Experimental data are consistent with a picture of an inner, unmixed core with ion temperature of ~ 3.4 keV surrounded by the colder mixed region with ion temperature of ~ 2.0 keV.

The goal of inertial confinement fusion (ICF) [1,2] is to implode a spherical target to achieve high compression of the deuterium-tritium (DT) fuel and high temperature in the hot spot, triggering ignition and producing significant thermonuclear energy gain. In indirectly driven laser designs [3], x-rays produced by the laser in high-Z enclosures (hohlraums) ablate spherical plastic capsules to implode inner layers of cryogenic DT fuel. To ignite the DT fuel and trigger a burn wave producing energy gain with a neutron yield above ~5e17 [3], the imploded fuel must achieve high compression to an areal-density of ~1.5 g/cm^2, while forming a high temperature (>5 keV) central hot-spot with areal-density of ~0.3 g/cm^2. The current point design at the National Ignition Facility (NIF) [3,4] uses a 1.6 MJ laser pulse at peak power of 410 TW to accelerate the DT fuel to a peak implosion velocity of ~360 km/s. However, simulations over-predict recent experimental DT fusion yields by factors of 3-10 [5,6]. Hydrodynamic instabilities and mix play a central role in the performance degradation; any drive asymmetries and surface imperfections are amplified by the hydrodynamic instabilities during implosion resulting in a distorted shell with reduced hot-spot temperature, pressure, and neutron yield [3]. The presence of mixed ablator material in the DT hot spot has been inferred in high-compression layered DT implosions [7,8], correlated with reduced experimental yields and temperatures relative to simulation predictions. Layered DT implosions have been modeled using 2D simulations intended to capture performance degradation due to instabilities and drive asymmetries [9-11]. The simulations modeled the measured surface roughness at all unstable interfaces, but did not predict atomic abtator-fuel mix [9]. While the simulations were close to explaining the performance of low-compression implosions (the DT neutron yields were within a factor of 2-3 from predictions), they were less accurate for high-compression implosions, in some instances over-predicting the yield by a factor of ~10. The discrepancies were especially pronounced in implosions with significant measured ablator-fuel mix [6].

It is crucial to better understand and mitigate the effects of hydrodynamic instabilities and mix, and to improve simulation predictions. This Letter describes implosion experiments that were designed to improve the ability to include atomic mix models [12] into 2D simulations and predict ablator-fuel mix. The experiments used capsules with plastic ablators including CD layers placed at various offsets from the inner surface of the shell. The capsules were filled with high-purity tritium gas to allow shell-gas atomic mix to be studied using the DT reaction (D + T $\rightarrow$ ^{4}He + n) by measuring DT neutron yield and ion temperature. This technique was previously used in direct-drive implosions of CD capsules on OMEGA [13], along with variations of this technique, one based on using ^{3}He gas and the D + ^{3}He $\rightarrow$ ^{4}He + p fusion reaction [14-17] to quantify the mixing of separated reactants, and another using H gas and D + D $\rightarrow$ ^{4}He + n fusion reaction [14-18] to measure how much ablator material reaches fusion temperatures. This Letter describes the first mix experiments in ignition-relevant conditions with indirect drive at a moderate convergence ratio of ~15 at NIF. The convergence was chosen to be about 2 times lower than in the layered DT implosions to reduce the high variability of the performance observed in the high-compression implosions. In addition to the DT reactions probing conditions in the mixed region, these experiments also employed TT reactions [19-21] to probe the inner-core region. This addition significantly constrained parameters in modeling.

Figure 1 shows the capsule schematic and the laser pulse used in these experiments. Plastic shells had a nominal 209-μm thickness and 2280-μm-initial outer diameter [5]. Si-doped layers were included to reduce preheat of the inner CH ablator from 2-4 keV M-band emission from the Au hohlraum wall [2]. The capsules for five implosions included a CD layer with 4.0-μm thickness, placed at either the inner shell surface, or offset by 1.2, 2.3, 3.9, and 8.0 μm from the inner surface by the CH-only layers. The shells were filled with tritium gas at mass density of 11.05 mg/cc and temperature of 32 K. The tritium gas included a small contamination of deuterium gas at 0.1% by atom fraction. The background DT yield from this D contamination was measured in two additional implosions that did not contain the CD layers. The DT reactions from these two control implosions were also used as a diagnostic of the central core ion temperature. All implosions used a laser pulse with peak power of ~435 TW and total laser energy of ~1.5 MJ; the same pulse was used in layered DT implosions yielding areal densities of ~1.0 g/cm^2 [5]. Details of the laser pulses, pointing, and hohlraum geometry were ascertained by previous experiments as described in Ref. [5]. The capsule and drive parameters were kept very similar in this set of experiments; deviations in capsule thickness and outer diameter from specifications were less than 0.5% and 1.5%, respectively, and the laser power was within ignition specifications [5] for all shots.

The surface roughness of the plastic capsule surfaces was comprehensively characterized. For all shots with a CD layer, the surfaces were similar and met specifications [5], while in two shots without CD layers the roughness in modes from 2 to 12 was up to ~2 times above the specification. The dust particles on the outer surface were also characterized before capsules were sealed in hohlraums. While experimental specifications required no single particle with a volume greater than 30 μm^3 to be present on a capsule surface [3], some shots had particles that exceeded this limit. In these experiments, the same rule was adopted as in the companion DT layered implosions [6], requiring no single particle with volume greater than 100 μm^3 to be present on a capsule surface, with total volume of all particles not exceeding 150 μm^3 in any rectangular area of 127 μm x 92 μm.

The performance of all implosions was characterized with a comprehensive set of nuclear and x-ray diagnostics [5, 22]. The x-ray fluxes of hohlraum radiation out the laser entrance hole were measured with the Dante detector [5]; the inferred x-ray flux temperatures were very repeatable, 294±4 eV in all shots. Measured implosion x-ray bang times were ~22.55±0.10 ns, all within 100 ps from each other, with the burn width ~300 ps in all shots. Figure 2 shows examples of the measured x-ray images of the target at bang time in the x-ray range above 8 keV with spatial resolution of ~10 μm and temporal resolution of 100 ps viewed in (a) the polar and (b) equatorial directions [23]. The images were good representations of all the implosions, showing nearly round x-ray emission at peak compression. The images show more structure than has been typical in “symcap” (plastic-gas implosions) images on NIF, because the hydrogen gas fill radiates less than the He that is typically used; the images accordingly highlight radiation from the hot higher Z carbon around the core. The 17% contours (relative to peak x-ray brightness) in both polar and equatorial directions had radii of ~60 μm, varying less than 10% from shot-to-shot. The low-mode hot-spot distortion specification was <10% rms [3] for the deviation from round of the 17% emission contour. All shots met this requirements; the x-ray shape was slightly prolate with mode P_2/P_0 ~0.1. The measured convergence ratio (defined as a ratio of the initial inner-capsule radius to the radius at peak burn) was about ~15, smaller than in high-compression layered implosions, which had convergence ratio of 28-30. The convergence was different, even though they were driven with the same drive and capsules had equivalent masses, due to the fact that the plastic capsules had both a higher initial gas fill pressure and a higher shell adiabat than layered DT capsules [24,25].

Figure 3 shows examples of the measured neutron spectra in implosions with and without CD layers. The peak at 14.1 MeV was used to measure both the total DT neutron yield and the ion temperature in the DT producing region, while neutrons below 9 MeV were used to measure TT yield in the central hot spot. Target compression was inferred using the down-scattered ratio (DSR ~1.2%) of scattered neutrons in the range from 10 to 12 MeV, relative to primary neutrons in the range from 13 to 15 MeV [26]. Simulations indicate that roughly half of the down-scattered neutrons were scattered in the tritium gas, while the other half are scattered by the plastic shell [3].

The experimental results were compared with 2D simulations using the code ARES [27]. As direct numerical simulation of hydrodynamic instabilities and turbulence were not possible, an approximate approach was made. To capture large wavelength low-mode (l <~ 100) instabilities, simulations were performed using an angular resolution of 1/8 degree, with imposed surface roughness at unstable interfaces. The K-L mix model (where K represents turbulent kinetic energy, and L is the spatial scale of the mixing layer) [12] was included to capture the turbulent regime and the effects of mix at scales smaller than the computational grid. The free parameter in this method was the initial turbulent mixing length, L_0, set at all unstable interfaces. When utilizing the K-L model in this way, care must be taken to insure that the mixing length L remains smaller than the grid scale to avoid 'double-counting' between the two methods.

In order to calibrate the simulations, a multiplier on the outer ablator surface roughness was varied. A multiplier of 3 times the NIF roughness specification in modes up to 100 was needed to match the measured conditions in the central core, as determined by the TT and DT yields and ion temperatures measured in the control capsules. This parameter was then held fixed for the capsules with CD layers. Figure 4 shows examples of the predicted products of the D and T number densities at peak burn for implosions with a non-recessed CD layer (upper half) and a ~2 μm recessed CD layer (lower half). This product is proportional to the DT reactivity at burn time, and shows the atomically mixed region where 14 MeV neutrons originate. Figure 5 shows the measured neutron results and comparisons with ARES simulations using three different values of the initial turbulent length scale, L_0=10 nm, L_0=0.5 nm, and L_0=0.1 nm. TT yields, DT ion temperatures, and DT yields are shown in Figs. 5 (a), (b), and (c), respectively. In implosions without CD layers (shown as "TT symcaps"), the measured TT and DT yields along with DT ion temperatures probed the same conditions in the central part of the core. In implosions with CD layers, the TT yields were similar to those in “TT symcaps”, while DT yields were higher (up to ~6 times), and DT ion temperatures were lower (~ 2.0 keV vs 3.4 keV). The lower measured temperature supported the hypothesis that the DT neutrons were primarily generated in the colder region where D and T were atomically mixed. As the recession of the CD layers from the inner surface increased, the measured DT yields decreased, indicating that much of the plastic mixed into the gas came from a region close to the inner surface as opposed to being transported from further out by hydrodynamic ‘spikes’.

It can be seen in figures 5(a) and (b) that the TT yield and DT ion temperature were relatively insensitive to the choice of the initial L_0. However, while all three sets of simulations do capture the trend in DT yield decrease with the CD recession depth, L_0=10 nm set over-predicts the experimental DT yields by factors of ~2, while the L_0=0.1 nm set slightly under-predicts them, as shown in Fig. 5(c). While the L_0=0.1 nm set would appear to be a better match, this may be due to phenomenological failings of the KL model; for instance, the L_0=10 nm case could accurately capture the mixing width but over-predict DT mix yields if process of atomic mixing is not instantaneous (as is assumed in the K-L mix model), but instead takes some finite time comparable to the experimental burn time of ~300 ps. Since the understanding of mixing is crucial for ignition designs, additional studies are required to gain better understanding of the atomization during ablator-gas mixing.

The measured outer surface roughness in these experiments varied from 0.5 to almost 2 times the NIF specification. Our simulations, assuming 3x the specification, thus vary from 2 to 6 times above the measured roughness. This need for a multiplier is consistent with previous 2D simulations of high-compression layered DT implosions, which require comparable surface roughness multipliers to match experimentally measured yields [9]. There are several possible explanations for needing a large multiplier. The Rayleigh-Taylor growth rates during the acceleration phase, or the pre-acceleration amplitudes set by the Richmyer-Meshkov instability could be larger than simulated [3]. Seeds to the instability growth are not fully captured in the simulations, and could be several times worse than we assume, particularly in 2D simulations. Some seeds, including radiation asymmetry and the effect of support tent discontinuity at lift-off [28] are not included in the simulations discussed here. And it is likely that 3D hydrodynamic effects are more deleterious than the 2D simulations described here. In any case, the resultant elevated modulations could cause stronger ablator-fuel mix and performance degradation at peak compression [3]. To study these processes, measurements of pre-imposed, ablation-front amplitudes using x-ray radiography are currently underway at NIF.

In conclusion, ablator-gas mix was studied using DT fusion reactions in implosions with plastic capsules including CD layers filled with tritium gas on NIF. Capsules were imploded with x-rays generated in hohlraums with peak radiation temperatures of ~294 eV, at a moderate convergence ratios of ~15. While neutrons from the TT fusion reactions probed conditions in the central part of the implosion core, the neutrons from the DT reactions probed the mixed region outside the core. Experimental data are consistent with a picture of an inner, unmixed core with ion temperature of ~ 3.4 keV surrounded by a colder mixed region with ion temperature of ~ 2.0 keV. 2D simulations (including a K-L mix model) needed 2-6 times increased levels of the surface roughness for the modes below 100 to match conditions in the central part of the core. In the outer part of the core, the ion temperatures were predicted close to experimentally measured. The absolute DT mix yields are sensitive to the initialization of the mix model, although the qualitative trends were similar to the experimental measurements.

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FIGURE CAPTIONS

FIG. 1. Pulse shape used in experiments with peak power of 436 TW. Schematic of the capsule with nominal outer diameter of 2264 μm, shell thickness of 209 μm, and a 4-μm thick CD layer, placed either at inner shell surface, or recessed form the inner surface by 1.18 and 2.27 μm of CH layers. The capsules were filled with tritium gas with mass density of 11.05 mg/cc at temperature of 32K.

FIG. 2. Measured time-integrated x-ray images of imploded core at x-ray photon energies above ~8 keV in (a) polar and (b) equatorial directions.

FIG. 3. Examples of measured neutron spectra with CD layer recessed by 0 μm (thick solid curve), 1.18 μm (thin solid curve), 2.27 μm (dashed curve), and without CD layer (dotted curve).

FIG. 4. The product of the deuterium density and tritium density for simulations with 0 μm recessed (upper half) and 2.27 μm recessed (bottom half) layers, showing spatial distribution of the shell-gas mix.

FIG. 5. Measured and simulated (a) TT neutron yield, (b) ion temperature inferred using DT fusion reaction, and (c) DT neutron yield, as a function of recession depth of the CD layer, and for "TT Symcaps" without CD layer. Results of 2D ARES simulations including K-L mix model are shown with three initial turbulent mixing lengths of L_0=10 nm (solid curve), L_0=0.5 nm (dashed curve), and L_0=0.1 nm (dotted curves).

Figure 1

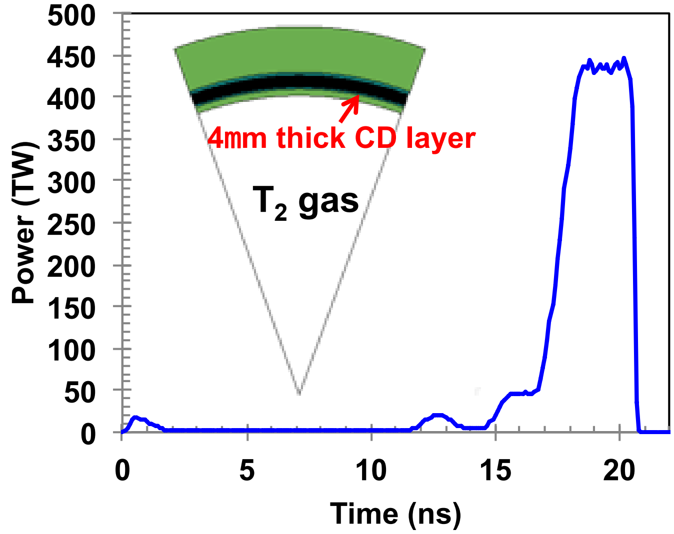

500
450
400
350
300
250
200
150
100
50
0
Power (TW)
4mm thick CD layer
T_2 gas
0
5
10
15
20
Time (ns)

Figure 2

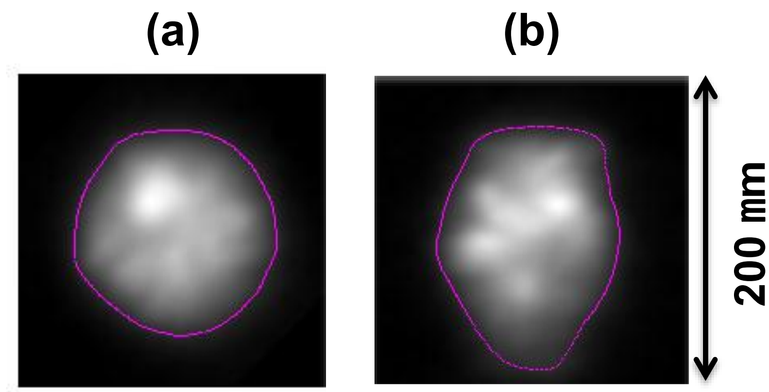
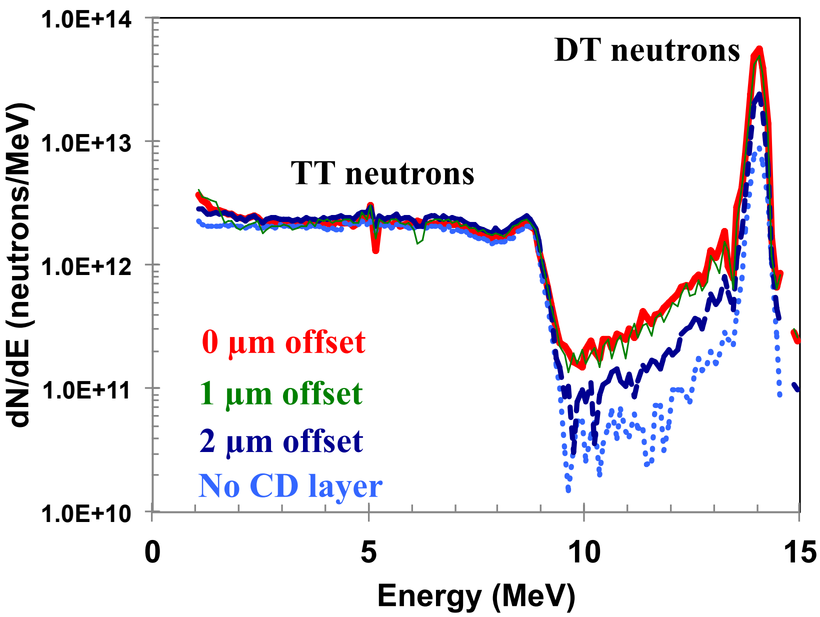


Figure 3



1.0E+14
1.0E+13
1.0E+12
1.0E+11
1.0E+10
dN/dE (neutrons/MeV)
DT neutrons
TT neutrons
0 µm offset
1 µm offset
2 µm offset
No CD layer
0
5
10
15
Energy (MeV)

Figure 4

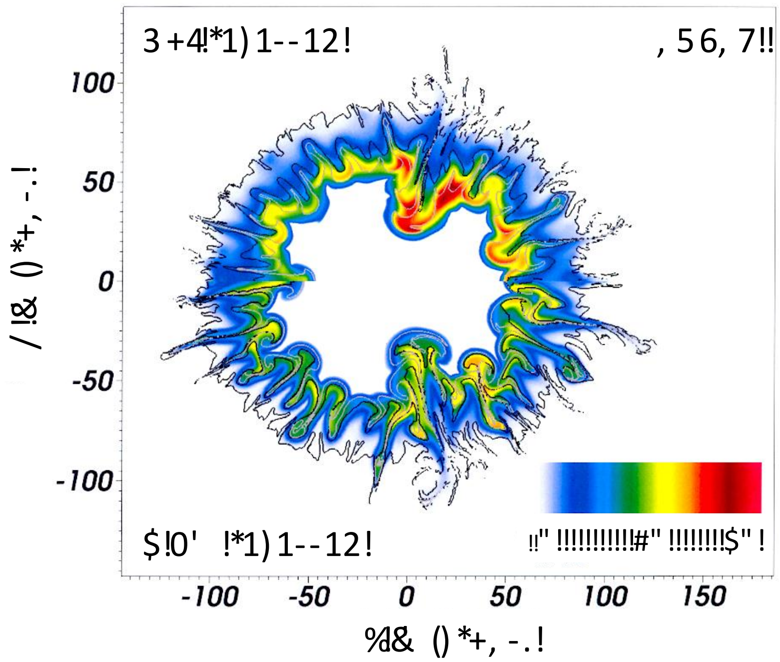
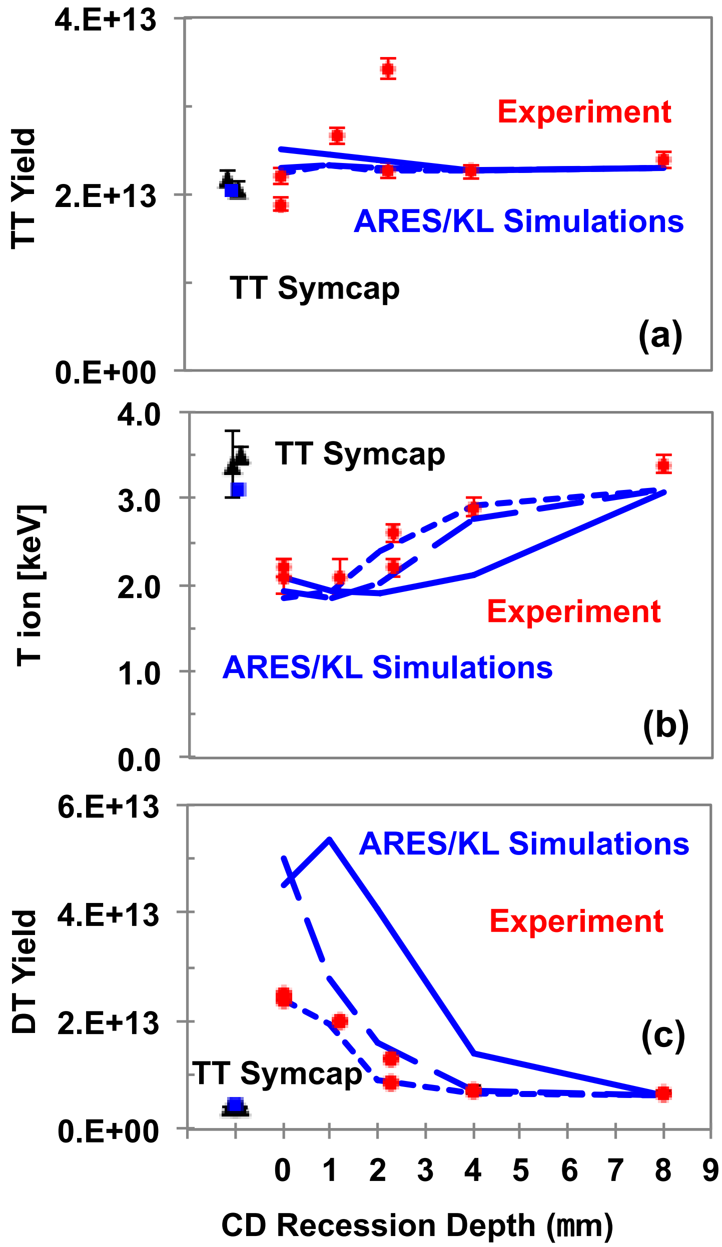


Figure 5


4.E+13
2.E+13
0.E+00
TT Yield
Experiment
ARES/KL Simulations
TT Symcap
(a)
4.0
3.0
2.0
1.0
0.0
T ion [keV]
TT Symcap
Experiment
ARES/KL Simulations
(b)
6.E+13
4.E+13
2.E+13
0.E+00
DT Yield
ARES/KL Simulations
Experiment
(c)
TT Symcap
0 1 2 3 4 5 6 7 8 9
CD Recession Depth (mm)